Resonance Region Structure Functions and the Transition to Perturbative QCD

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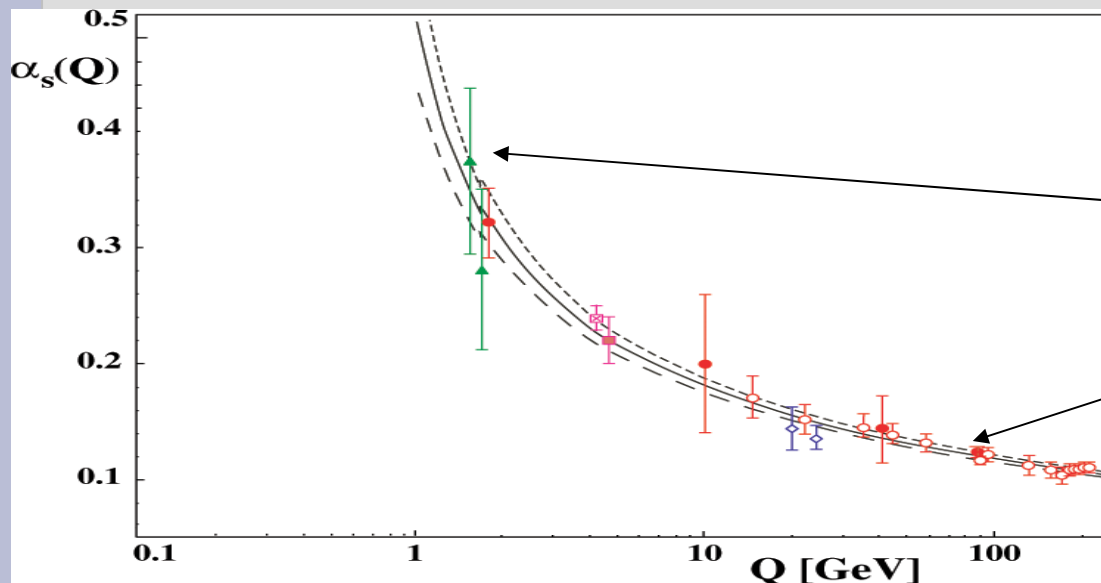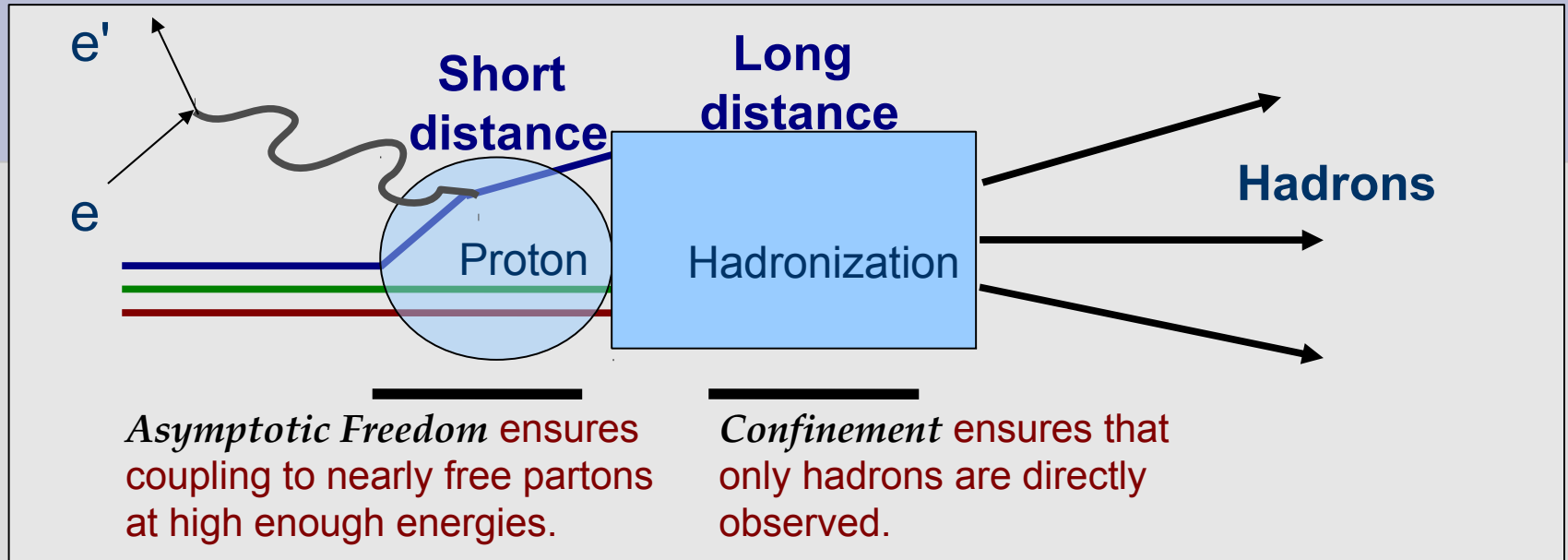
Hampton University

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When describing properties of hadrons:

1. At low energies effective theories with baryons and mesons as degrees of freedom often work well.

2. quarks and gluons are manifest at large energies as the fundamental constituents.

The transition between these 2 QCD regimes is *not* understood, and solutions to full QCD are limited to the Lattice in the non-perturbative regime.

Studying this transition is the goal of JLab

2 Defining Properties of QCD

e'

e

Short distance

Long distance

Proton

Hadronization

Hadrons

Asymptotic Freedom ensures coupling to nearly free partons at high enough energies.

Confinement ensures that only hadrons are directly observed.

$\alpha_s(Q)$

0.5

0.4

0.3

0.2

0.1

0.1   1   10   100
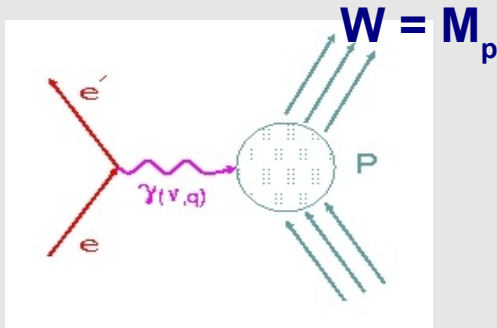
Q [GeV]

quarks are far apart

=> restoring force is large enough to pull qq pairs from vacuum.
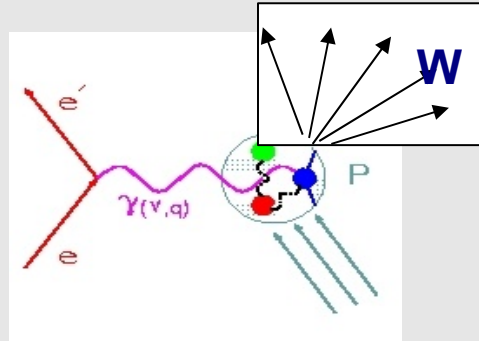
quarks are close (~< 1fm)

=> strong coupling is small

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* Inclusive Lepton Scattering allows for study of the transistion from non-perturbative to the perturbative regimes
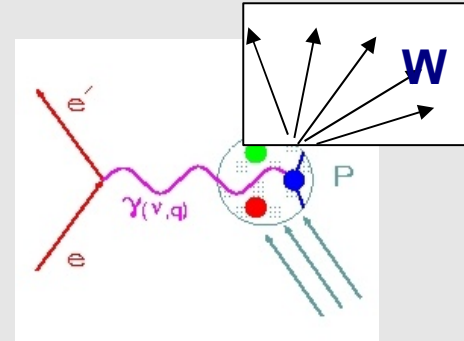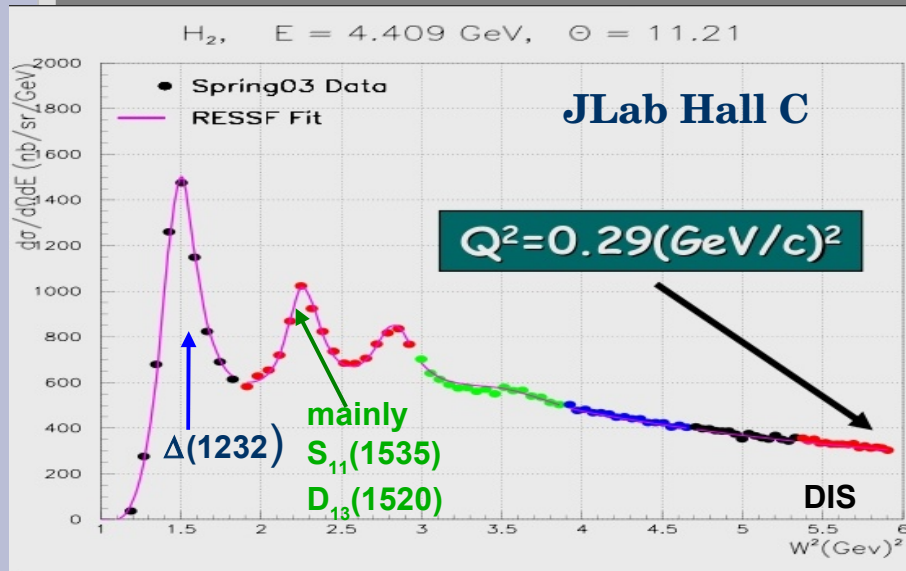
Elastic **Resonance** **Deep Inelastic**

$W = M_p$

W

W

$$\frac{d\sigma}{d\Omega\, dE'} \propto \Gamma\, [2xF_1(x,Q^2) + \varepsilon\, F_L(x,Q^2)]$$

$$F_L = (1+\nu^2/Q^2)F_2 - 2xF_1$$

H₂,   E = 4.409 GeV,   Θ = 11.21

- Spring03 Data
- RESSF Fit

JLab Hall C

$Q^2 = 0.29 (GeV/c)^2$

$\Delta(1232)$

mainly
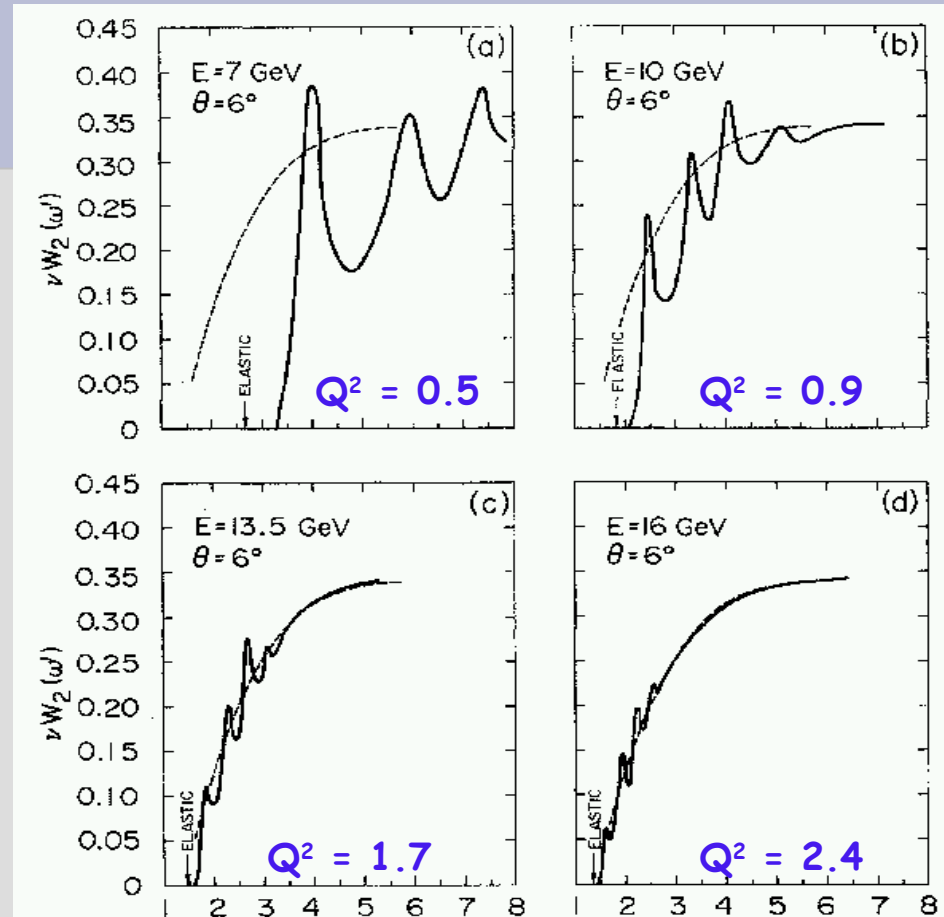$S_{11}(1535)$
$D_{13}(1520)$

DIS

Study the W (or x), Q² dependence of the structure functions from

Elastic → resonance excitation → DIS

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Quark-Hadron Duality - a reminder

▶ First observed by Bloom and Gilman At SLAC ~1970, prior to development of QCD.

▶ Noted that resonances oscillate around a 'scaling' curve at all Q^2.
- hadrons follow the DIS scaling behavior.

$\omega' = 1+W^2/Q^2$

Novel observation that was generally left unstudied for next 30 years.

Quark-Hadron Duality
complementarity between quark and hadron descriptions of observables

At high enough energy:

Hadronic Cross Sections averaged over appropriate energy range

$$\Sigma_{hadrons}$$

=

Perturbative (Quark-Gluon)

$$\Sigma_{quarks}$$

Can use either set of complete basis states to describe physical phenomena provided you sum over enough states

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Quark-Hadron Duality - today
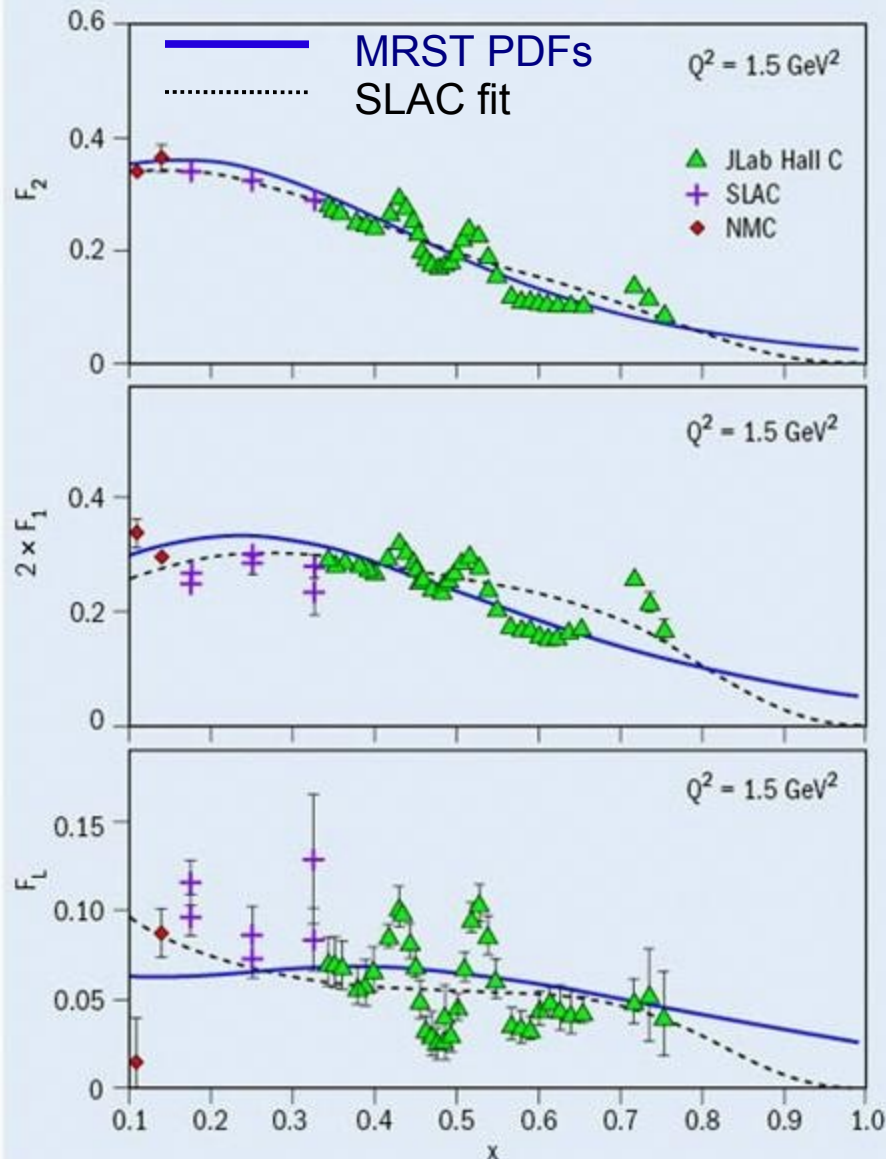
"The successful application of duality to extract known quantities suggests that it should also be possible to use it to extract quantities that are otherwise kinematically inaccessible."
(CERN Courier, December 2004)

Observed now in nuclei, semi-inclusive scattering, spin structure functions, separated L/T channels, sought in neutron structure (soon), neutrino scattering.

Fascinating link between hadron and quark phenomenology- challenges our understanding of strong interaction dynamics
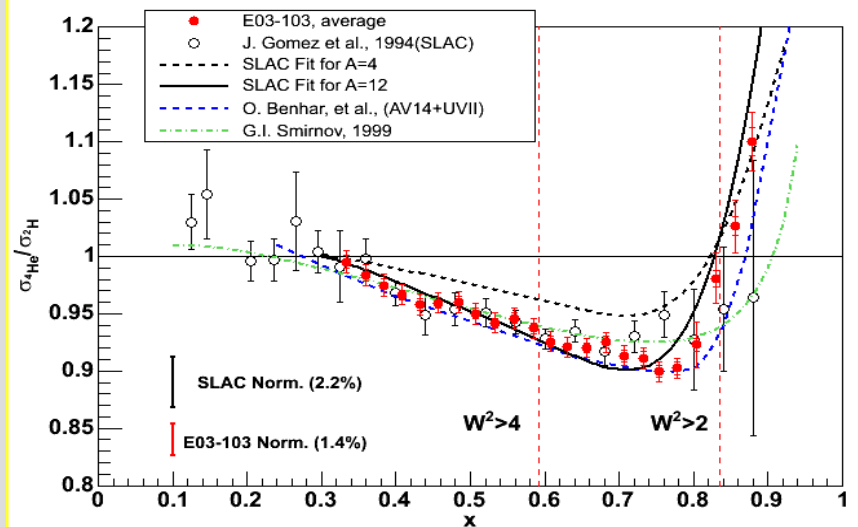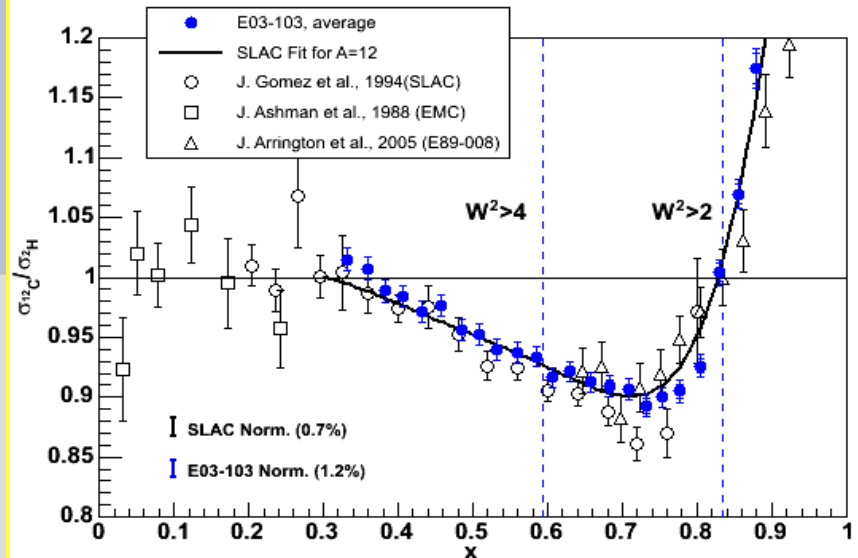
Tool to access large x regime?

Duality in Nuclei

$$\xi = 2x / [1 + (1 + 4M^2x^2/Q^2)^{1/2}]$$

p

d

Fe
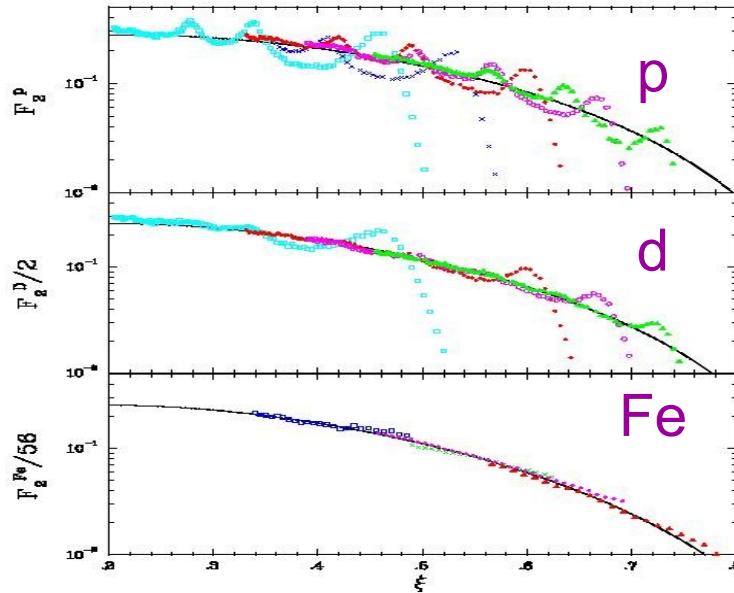
- Fermi motion in the nucleus accomplishes averaging in x, ξ.

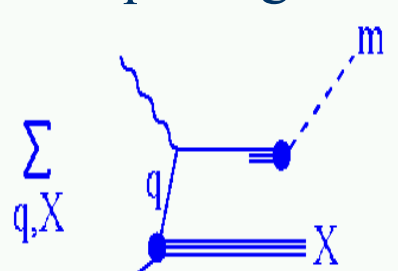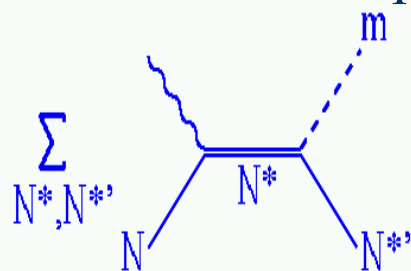=> Duality works even better in nuclei.

Duality is also observed in the EMC effect!

Duality in pion Electroproduction

hadronic description   quark-gluon

$$\sum_{N'^*}\left|\sum_{N^*} F_{\gamma^* N \to N^*}(Q^2, W^2)\, \mathcal{D}_{N^* \to N'^* M}(W^2, W'^2)\right|^2 \equiv \sum_q e_q^2\, q(x)\, D_{q \to M}(z)$$

Transition Form Factor   Decay Amplitude   Quark distribution q(x) X Fragmentation Function. D(z)

Parton model using fragmentation functions from DIS generally describes data well.

---- parton model assuming factorization

P$_{33}$(1232)
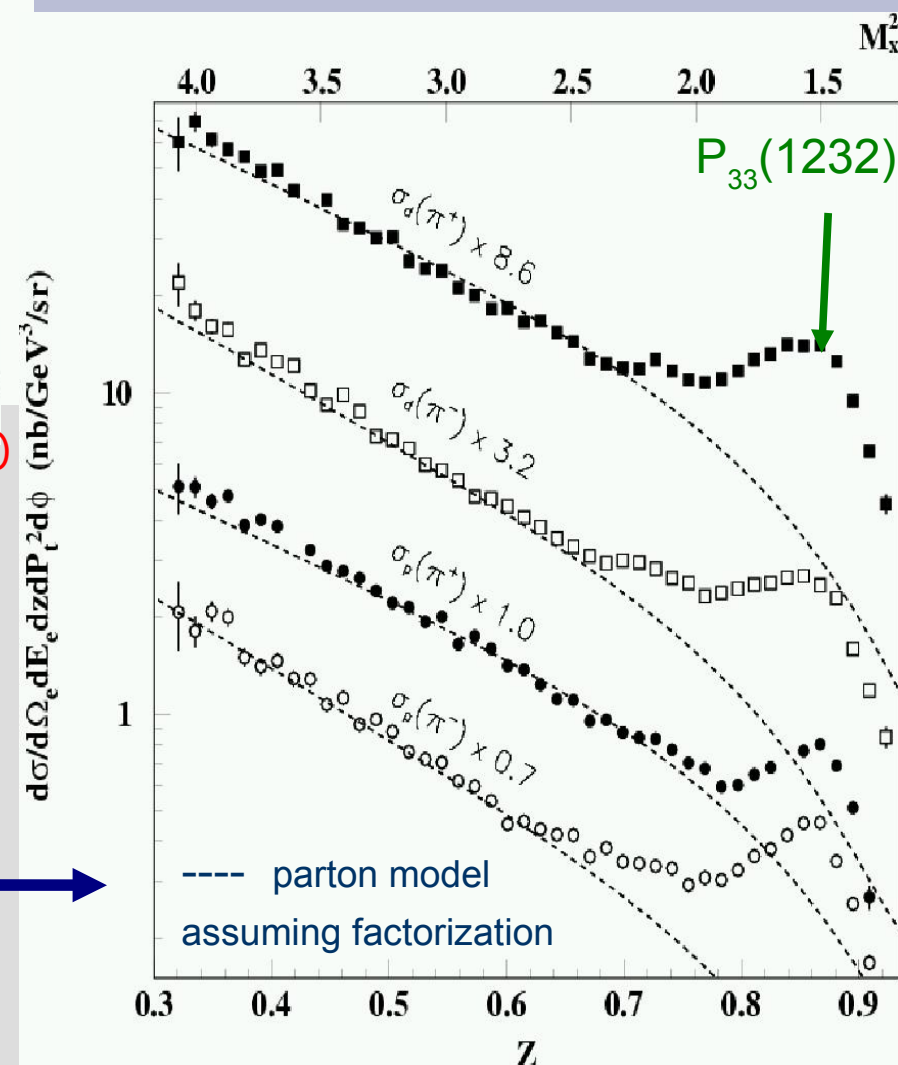
Exploratory theoretical studies of duality in $\nu - N$ scattering

O. Lalukulich, E. Paschos, W. Melnitchouk

→ **Resonance transition form factors were mainly determined from e-N (vector) and (rather poor) existing ν-N (axial) data (some model dependent assumptions)**

→ **Model missing non-resonant background and higher resonances.**
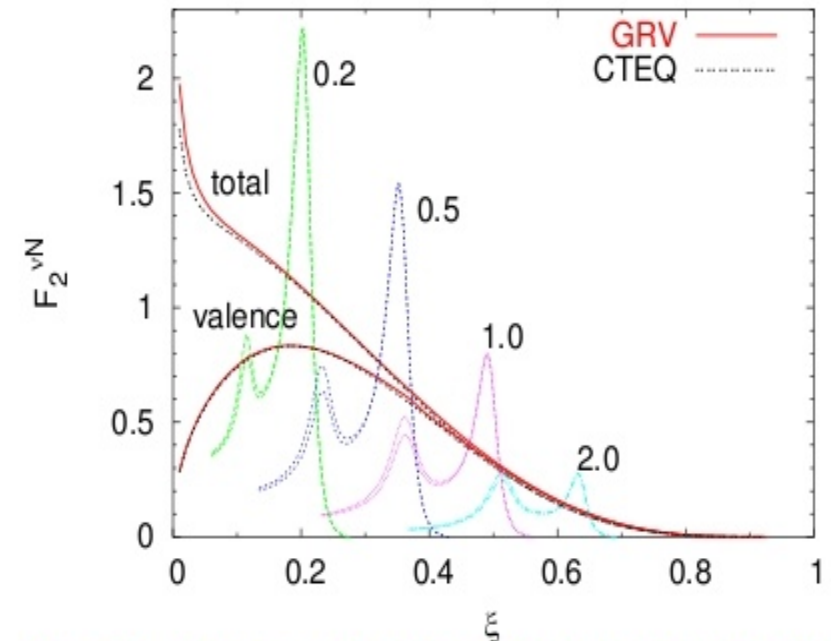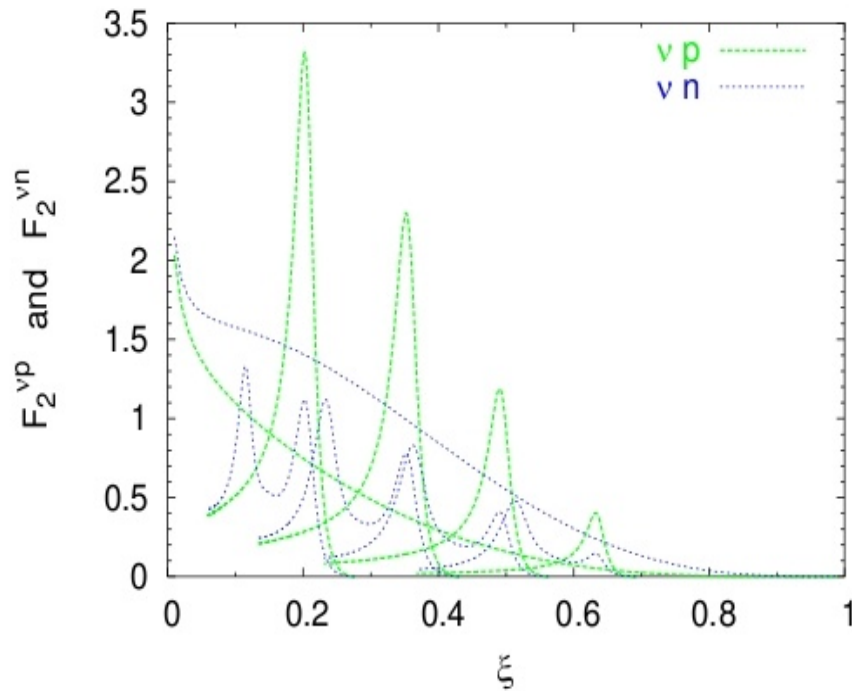
OL, E.A. Paschos, W. Melnitchouk, hep-ph/0608058

Exploratory Neutrino Conclusions:

1. duality not expected to be well obeyed in either

| ν-p | or | ν-n |

2. duality is expected to be obeyed to higher degree in

| ν-N (p+n)/2 | and | ν-A (isoscalar targets) |

* and also ν + νbar

Studies based on limited and lower precision ν data

→ MINERνA to provide higher precision ν data

on range of nuclear targets!

MINERνA will allow study of duality in ν-A scattering

3 years medium energy on Carbon, $Q^2 < (1 \text{ Gev/c})^2$

using E_{had} and P_μ ($\delta p/p \sim 10\%$) from MINERνA/MINOS

From TDR
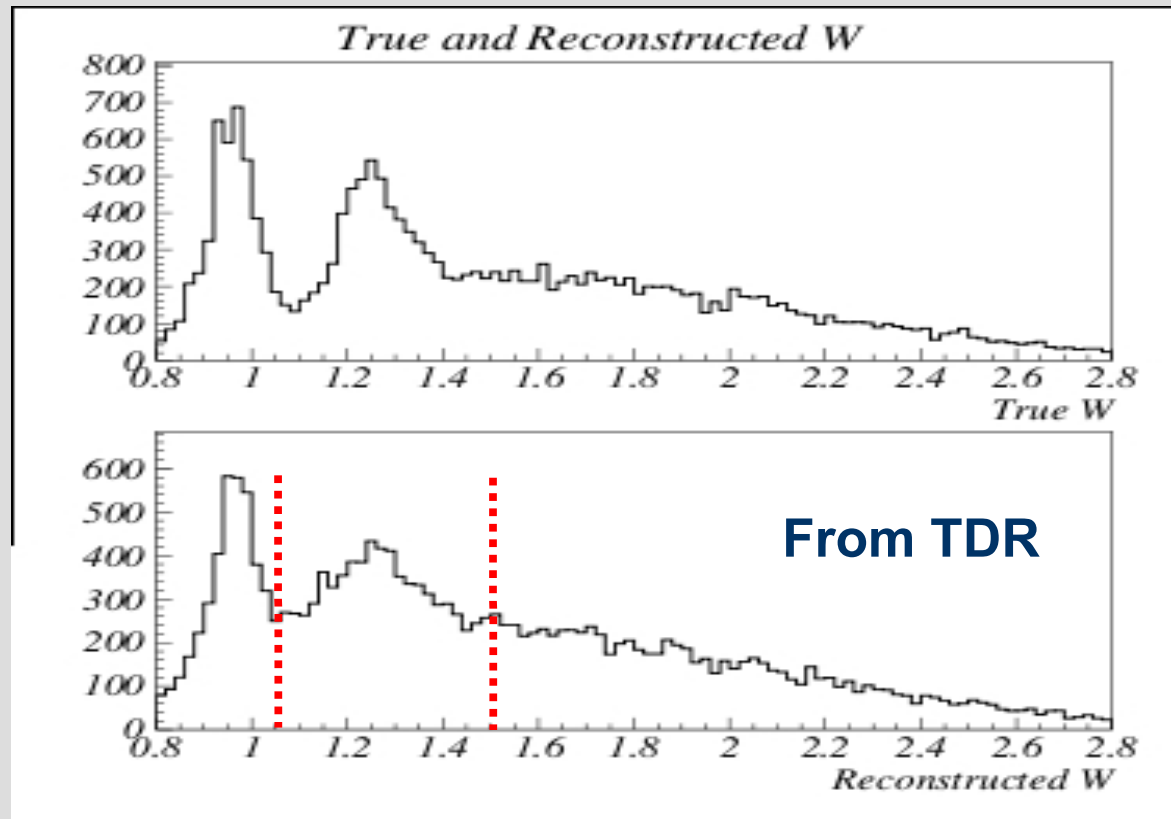
$N-\Delta^{++}(1232)$ transition

Carbon in MINERνA
- **3 years medium energy**
- **1 muon + 2 hadron tracks ($\Delta^{++}_{(1232)}$)**
- **1.1 < W < 1.5 GeV**
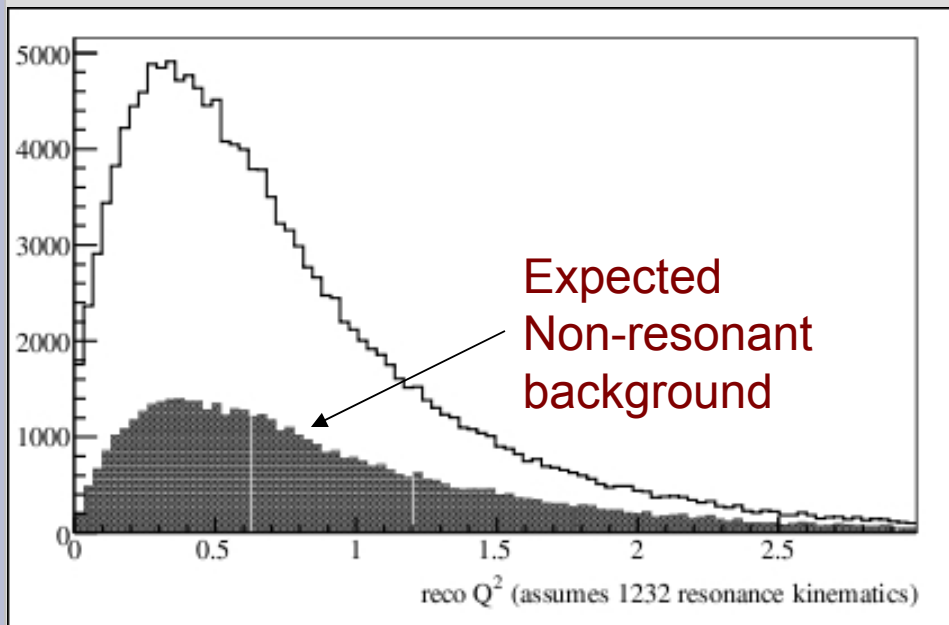
Model of Sato-Lee compared to BNL data

Expected Non-resonant background

reco Q^2 (assumes 1232 resonance kinematics)
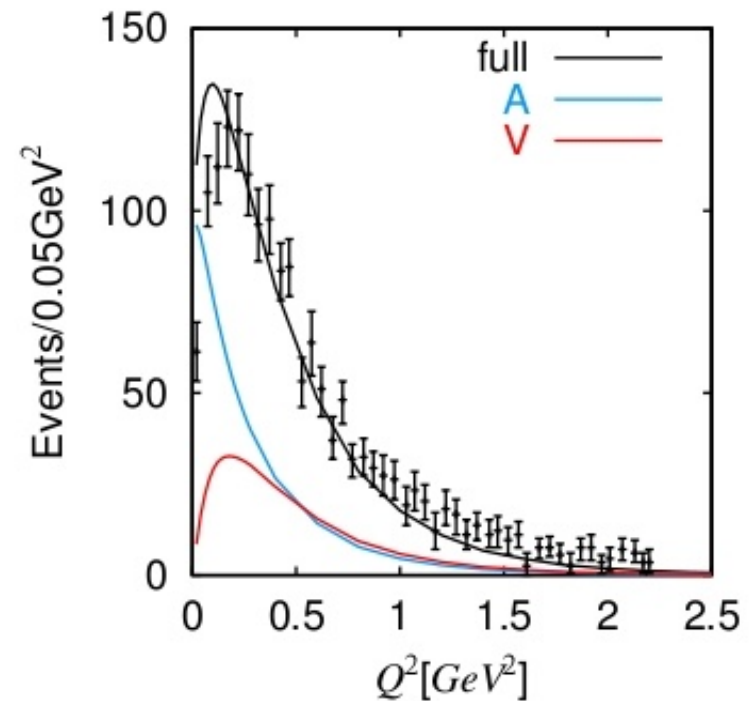
Duality still not understood

➢ **Does duality hold for ν-p, ν-n, and/or ν-N?**

➢ **Does global/local duality hold for $\nu-$scattering?**

➢ **If not, what resonance regions are outliers?**

➢ **Are nuclear effects in ν-A scattering the same**

for resonance excitation as the DIS?

Summary

➤ Study of nucleon resonances and transition form factors are vital for understanding nucleon structure within QCD.

➤ Quark-Hadron duality has been observed in many electron scattering processes and is evidently a fundamental property of QCD, but …

➤ We still don't understand the mechanism for duality, and

Measurements with a weak probe could provide an important piece of the puzzle!

Backup Slides

Dynamical model of Close/Isgur

→ Coupling to single quarks in baryon states

→ $F_2 \sim \Sigma \, e^2_q$ but Form factors $\sim (\Sigma \, e_q)^2$

→ Need enough even and odd parity states for $\sim e_i e_j$ terms to cancel

Destructive interference leads to factorization and duality

$SU(6)$ and $SU(3) \times SU(2)$ Multiplet Contributions to $\pi^{\pm}$ Photoproduction				
W'	$p(\gamma, \pi^+)W'$	$p(\gamma, \pi^-)W'$	$n(\gamma, \pi^+)W'$	$n(\gamma, \pi^-)W'$
56;8	100	0	0	25
56;10	32	24	96	8
70;^{2}8	64	0	0	16
70;^{4}8	16	0	0	4
70;^{2}10	4	3	12	1
Total	216	27	108	54

Predictions: Duality obtained by end of second resonance region
Factorization and approximate duality for $Q^2, W^2 < 3$ GeV^2

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Duality in pQCD

- Moments of the Structure Function

$$M_n(Q^2) = \int_0^1 dx\, x^{n-2} F(x,Q^2)$$

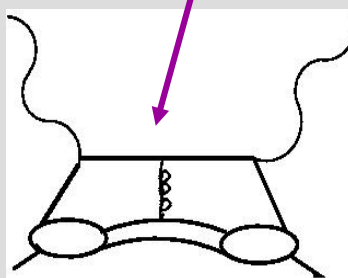For n = 2, this is the Bloom-Gilman duality integral!

- Operator Product Expansion

$$M_n(Q^2) = \sum_{k=1}^{\infty} (nM_0^2/Q^2)^{k-1} B_{nk}(Q^2)$$

higher twist   logarithmic dependence

(pQCD)

- Duality is described in the Operator Product Expansion *as higher twist effects being small or cancelling* **DeRujula, Georgi, Politzer (1977)**

Charged Lepton to neutrino DIS SFs

$$F_2^{eN} = 5/18x \, (\, u + \bar{u} + d + \bar{d} + 2/5s + 2/5 \, \bar{s} \,)$$

Same PDFs!

$$F_2^{\nu N} = \, x \, (\, u + \bar{u} + d + \bar{d} + s \, + \bar{s} \,)$$

If Duality works well in Nuclei then even the RR prescription for

$$\sigma^e_{res} \; -> \; \sigma^\nu_{res}$$

requires only PDFs and DIS nuclear corrections!

Do not need to know individual resonance couplings for inclusive cross sections!

At high energies: interactions between quarks and gluons become weak

 ("asymptotic freedom")

- efficient description of phenomena afforded in terms of quarks

At low energies: effects of confinement make strongly-coupled QCD highly non-perturbative

- collective degrees of freedom (mesons and baryons) more efficient

Duality between quark and hadron descriptions

reflects relationship between *confinement* and *asymptotic freedom*

Duality is intimately related to the transition from soft to hard QCD.